Thermal stability of a 4 meter primary reflector for the Scanning Microwave Limb Sounder

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Abstract*—We describe the fabrication and thermal-stability analysis and test of a composite demonstration model of the Scanning Microwave Limb Sounder (SMLS) primary reflector, having full 4m height and 1/3 the width planned for flight. SMLS is a space-borne heterodyne radiometer which will measure pressure, temperature and atmospheric constituents from thermal emission between 180 and 660 GHz. Current MLS instruments in low Earth orbit scan pencil-beam antennas (sized to resolve about one scale height) vertically over the atmospheric limb. SMLS, planned for the Global Atmospheric Composition Mission of the NRC Decadal Survey, adds azimuthal scanning for better horizontal and temporal resolution and coverage than typical orbit spacing provides. SMLS combines the wide scan range of the parabolic torus with unblocked offset Cassegrain optics. The resulting system is diffraction-limited in the vertical plane but highly astigmatic in the horizontal, having a beam aspect ratio ∼1:20. Symmetry about the nadir axis ensures that beam shape is nearly invariant over ±65° azimuth. The antenna feeds a low-noise SIS receiver whose FOV is swept over the reflector system by a small scanning mirror. Using finite-element models of antenna reflectors and structure, we evaluate thermal deformations and the resulting optical performance for 4 orbital environments and isothermal soak. We compare deformations with photogrammetric measurements made during wide-range (ambient+[-97,+75]° C) thermal soak tests of the primary in a chamber. This range exceeds predicted orbital soak ranges by large factors, implying in-orbit thermal stability of 0.21μm rms/°C, which meets SMLS requirements.

I. Introduction

The Scanning Microwave Limb Sounder (SMLS) instrument, planned for launch aboard the Decadal Survey's Global Atmospheric Composition Mission (GACM) mission, studies fast tropospheric processes using the microwave limb sounding technique, whose vertical resolution and cloud and aerosol penetration have already been demonstrated with current instruments (UARS and Aura MLS). While daily vertical profile observations from these satellite instruments have provided needed first-order information on the upper troposphere, they lack the spatial and temporal resolution required to quantify important smaller-scale processes that dominate this region's behavior on larger scales from regional to global.

The toric Cassegrain antenna developed for SMLS [1] provides azimuth-independent scanning over a $\pm 65^\circ$ swath of a conical scan (about the nadir axis) from the 830 km GACM orbit. Primary, secondary and tertiary surfaces are generated by rotating conic sections about a common toric axis in the nadir direction. Proper choice of the conic foci and the toric axis transforms a feed pattern with circular symmetry into a very narrow vertical illumination of the primary. The resulting footprint is diffraction limited in the limb vertical direction and $\sim 20\times$ broader, independent of azimuth, in the horizontal. A small (~ 10 cm diameter) mirror scans the beam over the antenna, while a slower $\sim 2^\circ$ nod of the entire antenna provides the vertical scan. Benefits to Earth science are dramatic improvements in temporal and spatial (lateral) resolution and coverage, which will propagate to the body of atmospheric science and become available for policy decisions pertaining to climate change and pollutant transport.

The objective of this study was to demonstrate fabrication of a 4 meter primary reflector for the toric Cassegrain antenna of SMLS in the GACM orbit. Fig. 1 shows the accommodation of SMLS on a conceptual GACM spacecraft and its illumination for a single azimuth pixel. We built a Graphite Fiber Reinforced Composite panel of size 4m x (1/3 width of flight SMLS), which provides full diffraction-limited performance of the center pixels of GACM SMLS. The reflector fabrication used a mold made in phase II of a NASA Small Business Innovative Research (SBIR) program by Vanguard Composites/DR Technologies, Inc.[2] The thermal stability test was developed from similar tests on communications antennas at lower frequencies, to verify figure performance under flight-like thermal environments using photogrammetric measurements. Finally, the task called for correlation of test results with finite element models developed by Vanguard and JPL, and prediction of in-orbit optical performance.

Our work plan split the $250K award in two parts: Vanguard received a $150K contract to fund fabrication and a thermal stability test of the reflector. The SBIR office granted additional funds matching this amount, enabling Vanguard to re-scope the deliverable test article from a 1 meter panel, originally proposed for phase II, to the 4×0.8 meter demonstration primary reflector. Section II describes the reflector fabrication, and Section III covers the thermal stability test. The remaining $100K was used at JPL for analysis and model development described in Section IV. These models were used to predict optical performance in both the candidate GACM orbits (for the full-size SMLS) and the thermal test of the demonstration reflector. Section V describes options to complete analysis of the thermal tests and continue developing the SMLS antenna.

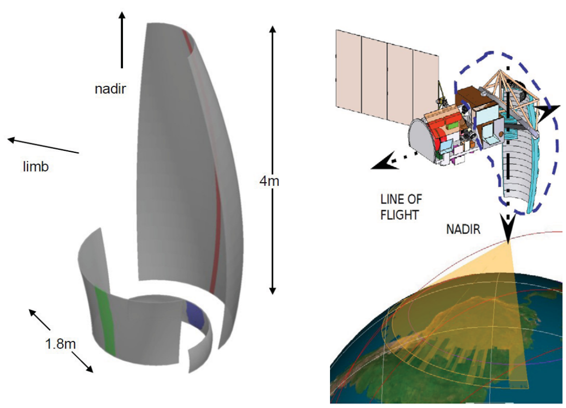

Fig. 1. SMLS antenna: (a) reflector illumination for a single azimuth pixel and (b) accommodation on GACM spacecraft.

II. Reflector Fabrication

As the SBIR program moved from phase I to phase II, several cost-saving measures were taken to bring the program closer to the anticipated requirements of SMLS. To achieve the figure accuracy needed for GACM SMLS at 640 GHz (a primary reflector with 12 μm surface figure) will require a large monolithic mold made of fine grain graphite, low-expansion glass, or Invar—all beyond the resources of an SBIR. However, we determined that the critical parts of the toric primary design could all be met with a demonstration reflector of the full 4 m height but only 1/3 the width. This would provide a full-size test article for future sub-aperture testing in a separate program.

We also relaxed the surface accuracy requirement ten-fold, to 120 μm rms, and separated the thermal stability requirement from the total accuracy budget. *I.E.* even with as-built figure errors much larger than a flight SMLS could tolerate, the thermal deformations we could measure would accurately indicate the thermal stability of the flight article. Moreover, by subjecting the reflector to a much larger range of soak temperatures than would be encountered in orbit, we could argue that the deformations measurable by conventional metrology techniques, such as photogrammetry, can be scaled down by the ratio of tested to flight soak difference. Hence we could infer the micron-level deformations a flight SMLS would undergo, using metrology techniques already proven for lower frequency large antennas.

The heritage of JPL's Aura MLS (operating from 118 to 660 GHz), coupled with recent improvements, led to the design, fabrication and text of the demonstration primary. Phase I of the SBIR produced a preliminary design having an all-composite design architecture with egg-crate core and front and rear face skins, to meet a total surface error budget of 12μm rms. It identified key material properties, notably near-zero in-plane face CTE and thermally conductive core laminate technology; these were achieved through pre-preg selection, tuning of materials, and standard lay-up and curing processes. Both the segmented core ribs and faceted back skin are planar elements to reduce parasitic mass, increase fundamental resonant frequency, and simplify design, analysis and assembly. For the core laminate, aluminum mesh was embedded in composite to raise thermal conductivity. Both front and rear skins were tiled to improve isotropy of material properties, especially CTE. Fig. 2 shows the 1/3xfull-height mold concept and a photograph of the latter stages of the demonstration reflector assembly with the core structure still visible before installation of the last back skin facet.

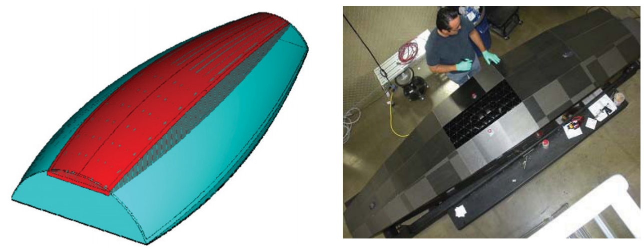

Fig. 2. SMLS antenna: (a) reflector mold, comparing center third used in the study (red) to full width required for SMLS (blue), and (b) installation of back skin facets over core in the reflector inverted on its mold.

Surface accuracy of the mold delivered to Vanguard was 41μm, *i.e.* 1/3 the specification but still 3 times as large as GACM SMLS will allow. Anticipating SMLS' need for improved metrology, Vanguard has begun to implement new techniques. One of these, developed by Burge at University of Arizona[3], uses the differential measurement mode of laser trackers for micron-level surface measurement. Vanguard has made preliminary comparisons between prior mold measurements by Coordinate Measuring Machine (CMM) and surveys of the reflector by laser tracker and photogrammetry. These show reasonable agreement and promise to provide the accuracy a flight SMLS will require. Another optical technique, speckle interferometry, was explored briefly in phase I of the SBIR and is available in JPL's Large Aperture Facility for further thermal testing described below.

III. Thermal Stability Test

Thermal stability testing in air was performed over several days in a chamber at Wyle Labs. Test methodology followed that of Thermo-Elastic Distortion (TED) tests performed on many previous Vanguard communications antennas. The profile began with a 6-hour dry-out at 90°C followed by holds, typically 1 hour long, at plateaus down to -120°C. At each plateau photogrammetry measurements were performed, rotating the reflector and using dual viewports to develop 3-D data sets. Fig. 3 shows the reflector configured for test.

The photogrammetric bundling accuracy ranged from 13 to 50μm at the hot and cold extrema, respectively, indicating measurement accuracy comparable to other reflector tests. Fig. 4 shows surface distortion maps at two plateaus; residuals from best-fit focal lengths are 0.0015 inch at ambient and 0.0011 inch at -100°C.

The SBIR final report gives factors of 3.7 (for 1500 km orbit) and 6.8 (for 800 km orbit) by which the *specific change*

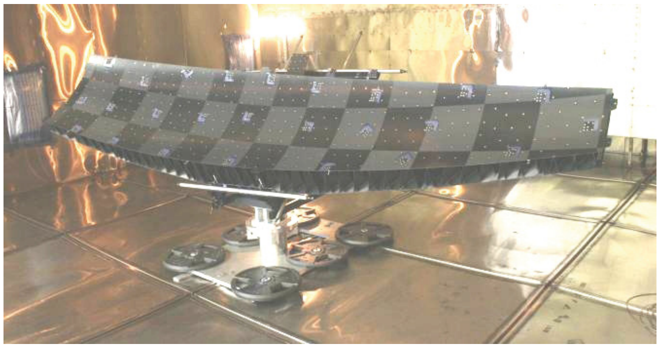

Fig. 3. Demonstration reflector with photogrammetry targets in thermal stability test chamber

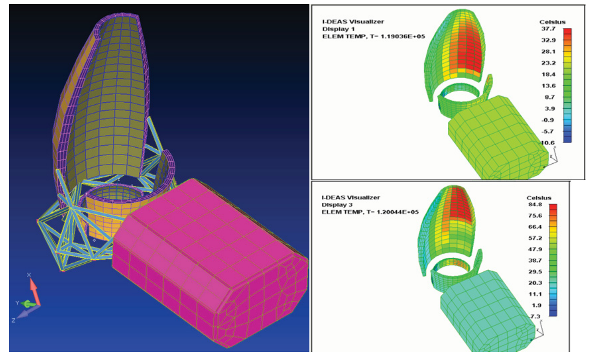

Fig. 5. Finite element model: (a) I-deas CAD model and (b) temperatures at two times in $\beta = 45°$ orbit.

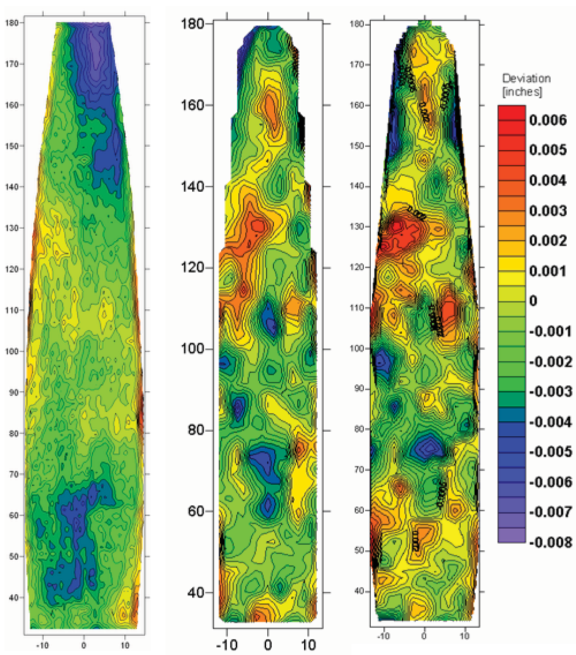

Fig. 4. Surface distortions: (a) mold; (b) reflector at ambient temperature and (c) $-100°$C, all expressed as half-Optical Path Difference (OPD/2). (a) was obtained from coordinate measurement machine by the mold vendor, (b) and (c) by photogrammetry during the TED test.

in surface accuracy (units of μm rms/°C) should be scaled to infer orbital performance from TED test deformations. Since the current goal for SMLS allows 3 μm rms of error due to 28–51° C temperature soak (*i.e.* 0.059–0.11 μm rms /° C), we deem the design associated with the 1.6 μm rms prediction due to -120° C (*i.e.* 0.13 μm rms /° C) is acceptable from a thermal distortion perspective.

IV. Predicted Performance in Orbit

We updated the thermal, structural and optical models, used in a 2006 study of the feasibility of a 4 m SMLS antenna in mid-Earth orbit ($h = 1500$ km) with 52° inclination, to the GACM orbit. Significant reduction in the temperature excursion results from a longer eclipse time in the low Earth orbit ($h = 1500$ km), improving optical performance.

We also extended our models to include secondary and tertiary reflectors, and support structure. For this study we assigned materials properties of the composite primary to the additional components; this is reasonable based on UARS and Aura MLS experience[4], where the contributions from aluminum secondary and tertiary were found to be much smaller than from the composite primary and support structure despite the CTE difference. A notional spacecraft bus was added to the model to simulate varying shading of the reflectors as the solar illumination evolves with orbit angle.

Fig. 5 shows the finite element model and the temperature distribution on reflectors. As in the 2006 study, the worst-case values of solar β, orbit time and pixel azimuth are determined more by self-shadowing of the primary reflector than by entry/exit of Earth's shadow.

Optical performance in the presence of surface deformations is calculated using a ray-based algorithm which calculate the Optical Path Difference (OPD) at each node for which deformations are provided. This method has been used for many previous reflector antenna systems[4] and is compatible with more refined models based on Physical Optics. The OPD is calculated with respect to a fixed feed point near the toric axis, tertiary and azimuth scanning reflectors. We expect similar results from subsequent models refined to include the much smaller reflectors used to direct the beam from the antenna into the radiometer box.

Fig. 6 shows OPDs from all three reflectors for a representative worst case time in the $\beta = 45°$ orbit, referred to the primary aperture. The location of largest OPD corresponds to the hottest point on the reflector seen in Fig. 5, even accounting for the varying stiffness and incidence angle embodied in the structural model. Table I gives the contributions of each reflector to maximum, minimum and rms OPD for the worst pixel at this time, showing that secondary and tertiary reflector deformations contribute significantly to optical performance (though less than the primary). The spatial and temporal distribution of rms OPDs suggest that deformations contribute more to pixel pointing more than to beam shape, which in turn implies that a tractable pattern correction could be applied in on-orbit data processing.

Fig. 7 plots three metrics of FOV performance (Limb

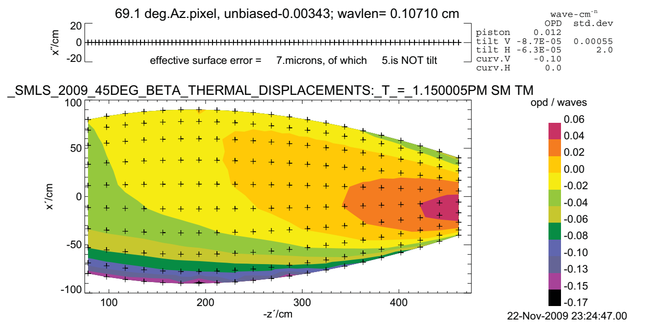

Fig. 6. Optical Path Difference (OPD) map at worst time in $\beta = 45°$ orbit

TABLE I
REFLECTOR CONTRIBUTIONS TO OPD FOR -23° AZIMUTH PIXEL

reflectors included			Optical Path Difference (waves)		
			min	max	rms
PM	SM	TM	-0.0405	0.0534	0.0242
PM			-0.0107	0.0740	0.0223
	SM		-0.0125	0.0011	0.0035
		TM	-0.0216	-0.0130	0.0019

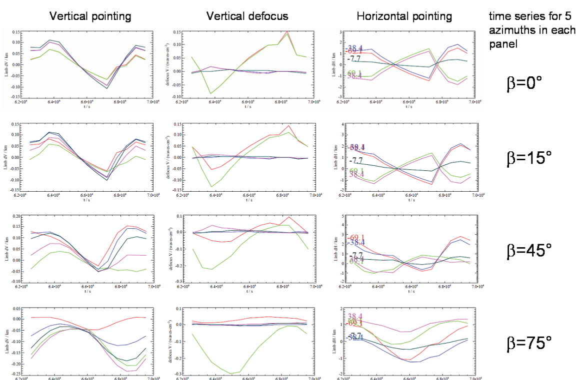

Fig. 7. Performance at 4 solar β angles in 830 km GACM orbit

Vertical pointing and defocus, and Limb Horizontal pointing) for all 4 solar β angles studied, each as 1-orbit time series for 5 pixels spanning the $\pm 65°$ azimuth width.

We also modified JPL's structural model to match the 1/3-width primary in the TED test, and updated material properties to final values provided by Vanguard. Using this model we calculated deformations for 1°C soak, 53% $\rightarrow$ 0% relative humidity dryout, and 1G loads in three orthogonal directions. Since the model is linear in each of these excitations, we have also modified the model data flow to scale FEM results to the TED test conditions described above, for comparison with the deformations measured by photogrammetry. Deformations of the JPL model were compared visually with those of the Vanguard model. We expect to complete data correlation with models in future programs.

V. Future Work

Much work remains to be done to prepare the SMLS antenna for inclusion in a flight instrument planned for GACM in the Decadal Survey program. Proposed programs to advance the readiness of the SMLS antenna begin with correlation of finite element models with CTE measurements of residual coupons from this program, and with the photogrammetric measurements of the TED test. More specific testing for thermal gradients expected in orbit can be performed in JPL's Large Deployable Aperture Facility, using local heat sources and in-house metrology systems such as the speckle interferometer and laser trackers available at the facility.

Vanguard has studied ways to produce a full-size reflector with low surface error using some combination of the current mold (either enhanced by surface machining or replaced with a finer grain or Invar mold) with assembly and alignment fixture which would allow 3 panels made from the current size mold to be joined into a full-width SMLS primary. Finally, the demonstration reflector could be the centerpiece of a breadboard antenna, with secondary and tertiary reflectors of appropriate materials to be tested on a Near Field Range at JPL at frequencies appropriate for the total surface accuracy; the 41μm rms of this reflector would allow testing at as low as 60 GHz, which gives a meaningful test of the toric antenna concept without unduly large Ruze tolerance losses. These options are components of an Instrument Incubator Program proposal currently being prepared.

VI. Conclusion

This study and the associated SBIR succeeded in validating the math models, design and fabrication of a breadboard primary for SMLS. Thermal stability test results indicate that SMLS performance requirements can be met with the composite design, and the demonstration reflector offers opportunities for advancing the flight readiness of the SMLS antenna.

Acknowledgment

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